IMPERIAL COLLEGE LONDON

Department of Earth Science and Engineering

Centre for Petroleum Studies

MODEL GRIDDING OPTIMIZATION FOR AN OIL RIM DEVELOPMENT IN THE NORTH SEA SUBJECT TO GAS AND WATER CONING

In cooperation with

Total e&p norge as

By

Arthur Auxenfants

A report in perfect fulfilment of the requirements for MSc and/or the DIC.

September 2013
DECLARATION OF OWN WORK

I declare that this thesis

“Model Gridding Optimization for an Oil Rim Development in the North Sea Subject to Gas and Water Coning”

is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

Signature:..............................................................................................................

Name of student:  Arthur AUXENFANTS

Name of supervisors:  Jamal KACER and Olivier GOSSELIN
A lot of reservoirs consisting of thin oil rims sandwiched between a gas cap and an aquifer have become valuable reserves since the appearance of horizontal well technology. These wells have a greater exposure to the reservoir sands and spread the pressure drawdown along their whole length, consequently reducing coning phenomena from the gas cap and from the underlying water.

Indeed, producing thin oil rims requires completing horizontal wells in the vicinity of contacts. Water and gas cones can be stable when wells are produced at low rates, or unstable when the cone reaches the well when produced above the critical rate. Because the economical constraints require producing at high rates, usually at supercritical rates, oil rim production is generally subject to water and gas coning, and recoveries are known to be highly dependent on production strategies. In that context, reservoir simulation has proven to be useful from well design to forecasting in order to achieve an optimized management of water and gas production.

This paper summarizes a study on a Total-operated field in the North Sea. This reservoir consists of a thin oil rim located between a small gas cap and a large aquifer. Because of the high viscosity oil in this reservoir, the production is assumed to be highly impacted by the gas and water coning to the horizontal wells completed within the oil rim.

A predictive model in which the grid is following the stratigraphy of the reservoir has been used for well design optimization. Yet this stratigraphic model happens to have drawbacks as it can lead to poor representation of water and gas flows as well as contact representations - both of them being crucial in the production management of an oil rim. Indeed, dipping cells in a thin oil rim lead to a lack of vertical resolution resulting in early water or gas breakthrough prediction (numerical dispersion, poor representation of horizontal wells…).

On the contrary, a horizontal grid allows a precise initialization of the model in the vicinity of the contacts and manages to represent their evolution better. Nevertheless, horizontal grids convey difficulties to represent reservoir heterogeneities – heterogeneities that in our case are importantly delaying water and gas fingering to wells. Furthermore, horizontal cells representation of dipping layers is also known to reduce connectivity due to the “stair-casing” effect.

The idea of this study is to run the development strategy on an optimized hybrid grid model gathering both horizontal and stratigraphic grids strengths. It relies on the horizontal gridding of the oil rim zone while keeping a stratigraphic grid in both the gas cap and the aquifer, to assess the impact of a coning-focused model on the recovery factor.
ACKNOWLEDGEMENTS

I would like to express my gratitude to Ata Nepesov for his technical expertise and his precious advice.

I thank TOTAL E&P NORGE A.S. for giving me the opportunity to carry out this study.

I would also like to address special thanks to Jamal Kacer and Thomas Bognø for their availability and the constructive advice that they provided.
TABLE OF CONTENTS

DECLARATION OF OWN WORK ............................................................................................................................ i
ABSTRACT .......................................................................................................................................................... ii
ACKNOWLEDGEMENTS ................................................................................................................................. iii
LIST OF FIGURES ............................................................................................................................................... v
LIST OF TABLES .................................................................................................................................................. vi
Abstract .......................................................................................................................................................... 1
Introduction ....................................................................................................................................................... 1
Literature review ............................................................................................................................................... 2
Reservoir background and reservoir modelling ................................................................................................. 2
Local Grid Refinements ................................................................................................................................... 3
Static and Dynamic hybrid model fitting ......................................................................................................... 4
  Initial water saturation .................................................................................................................................... 4
  Relative permeability ...................................................................................................................................... 4
Hybrid grid construction workflow ................................................................................................................ 6
Hybrid grid implications ..................................................................................................................................... 8
  Well definition ................................................................................................................................................. 8
  Transition zone and contact definition .......................................................................................................... 8
  Pinch-out layers .......................................................................................................................................... 8
  Stair-casing effect ....................................................................................................................................... 9
Properties remapping ......................................................................................................................................... 9
  Porosity and facies remapping ....................................................................................................................... 9
  Permeability remapping ............................................................................................................................... 10
Simulation results .............................................................................................................................................. 11
  Results analysis ........................................................................................................................................... 11
  Results discussion .................................................................................................................................... 13
Conclusion ......................................................................................................................................................... 14
Way forward ..................................................................................................................................................... 15
Acknowledgements ......................................................................................................................................... 15
References ......................................................................................................................................................... 15
APPENDICES ................................................................................................................................................... 16
  LITERATURE REVIEW APPENDIX .................................................................................................................. 16

iv
LIST OF FIGURES

Figure 1 - Facies property on a reservoir cross section ................................................................. 2
Figure 2 - Identified coning features on streamlines post processing on the stratigraphic model ............. 3
Figure 3 - Horizontal (left) and vertical LGR (right) on the oil rim scale ........................................... 3
Figure 4 - Full field early time recoveries on oil rim scale LGR runs (vertical LGR in orange, horizontal LGR in green and red) ............................................................................. 3
Figure 5 - Well 3 water cone development on coarse and horizontally refined models sections ................. 4
Figure 6 - Well 3 and 4 early water cut evolution .............................................................................. 4
Figure 7 - Top: Comparison original and reviewed Initial water saturation vs Height above FWL (Top) $S_{wc}$ vs Height above FWL (Bottom) ..................................................................................... 5
Figure 8 - Field results comparison with and without initialization and relative permeability revisions (solid lines stand for revised run) ....................................................................................... 6
Figure 9 - Stratigraphic and hybrid grids horizon structure on a full field section .................................... 7
Figure 10 - Improved zone definition for hybrid model on a full field section .......................................... 7
Figure 11 - Improved layering process for hybrid model ...................................................................... 7
Figure 12 - Well 3 completion depth in Stratigraphic and hybrid grids (left), Initial water saturations in the hybrid model (right) ........................................................................................................... 8
Figure 13 - Pinch-out layers on the coarse HYB1 (left) and HYB3 (right) .................................................. 8
Figure 14 - Refinement process for enhanced remapping ....................................................................... 9
Figure 15 - Comparison of porosity grids for different grids ................................................................ 10
Figure 16 - Sector model streamline results comparison between HYB3 permeability grids and HYB5 reference ....................................................................................................................... 11
Figure 17 - Full field results comparison between final HYB3 model (solid lines) and stratigraphic model (dotted lines) ................................................................. 12
Figure 18 - Well 2 sections with shale baffle representation on both stratigraphic and hybrid model and ternary representation of fluids after 2 months of production .............................................................................. 12
Figure 19 - Left: Qualitative water cut vs liquid cumulative comparisons to Helder and Troll wells. Right: Well 3 GOR and Water Cut .............................................................................................. 13
Figure 20 - Dimensionless WOR vs dimensionless time hybrid model results comparison with real field data ................................................................. 14
LIST OF TABLES

Table 1 - Grid sizes and running times ................................................................. 10
Table 2 - Compared well’s reservoir characteristics ........................................ 13
Model Gridding Optimization for an Oil Rim Development in the North Sea
Subject to Gas and Water Coning
Arthur Auxenfants, TOTAL E&P NORGE A.S., Imperial College London

Abstract
A lot of reservoirs consisting of thin oil rims sandwiched between a gas cap and an aquifer have become valuable reserves since the appearance of horizontal well technology. These wells have a greater exposure to the reservoir sands and spread the pressure drawdown along their whole length, consequently reducing coning phenomena from the gas cap and from the underlying water.

Indeed, producing thin oil rims requires completing horizontal wells in the vicinity of contacts. Water and gas cones can be stable when wells are produced at low rates, or unstable when the cone reaches the well when produced above the critical rate. Because the economical constraints require producing at high rates, usually at supercritical rates, oil rim production is generally subject to water and gas coning, and recoveries are known to be highly dependent on production strategies. In that context, reservoir simulation has proven to be useful from well design to forecasting in order to achieve an optimized management of water and gas production.

This paper summarizes a study on a Total-operated field in the North Sea. This reservoir consists of a thin oil rim located between a small gas cap and a large aquifer. Because of the high viscosity oil in this reservoir, the production is assumed to be highly impacted by the gas and water coning to the horizontal wells completed within the oil rim.

A predictive model in which the grid is following the stratigraphy of the reservoir has been used for well design optimization. Yet this stratigraphic model happens to have drawbacks as it can lead to poor representation of water and gas flows as well as contact representations - both of them being crucial in the production management of an oil rim. Indeed, dipping cells in a thin oil rim lead to a lack of vertical resolution resulting in early water or gas breakthrough prediction (numerical dispersion, poor representation of horizontal wells...).

On the contrary, a horizontal grid allows a precise initialization of the model in the vicinity of the contacts and manages to represent their evolution better. Nevertheless, horizontal grids convey difficulties to represent reservoir heterogeneities – heterogeneities that in our case are importantly delaying water and gas fingering to wells. Furthermore, horizontal cells representation of dipping layers is also known to reduce connectivity due to the “stair-casing” effect.

The idea of this study is to run the development strategy on an optimized hybrid grid model gathering both horizontal and stratigraphic grids strengths. It relies on the horizontal gridding of the oil rim zone while keeping a stratigraphic grid in both the gas cap and the aquifer, to assess the impact of a coning-focused model on the recovery factor.

Introduction
The concerned formation is a sandstone reservoir containing a saturated oil rim below a small gas cap. The oil rim is 21m thick and because of the small size of the gas cap, the reservoir is mainly pressure supported by its aquifer. The viscosity of the oil is quite high (4cp) and its density close to the water density. For those reasons, the production of the oil is subject to water and gas coning, with gas cap evacuation being part of the early production strategy.

The production strategy is aiming at a fast oil recovery involving high liquid rates. An efficient way to reduce coning effects by limiting the drawdown is the use of long horizontal drains. The development strategy in our case involves 4 horizontal wells completed in the oil rim producing at supercritical rates (gas and water cones are unstable and reach the producing wells). Due to the limitation of surface processing facilities, estimating the evolution of the water rates involved is a key point in the well placement optimization and the forecasting process.

The existing reservoir model has a stratigraphic architecture (stratigraphic grid), meaning that the grid layering is following the geological stratification of the reservoir. Although this description allows reservoir heterogeneities (important in the reservoir dynamics) to be properly represented, the vertical resolution of the model in dipping cells is low. Consequently, water movements as well as contacts (from the initialization) could be more accurately modelled.

In this study, alternative gridding have been considered to improve flows and coning representation to the wells. Local Grid Refinements (LGR), in the vicinity of wells or in the entire the oil rim, is an easy way to gain resolution while keeping a stratigraphic grid and has been investigated. Horizontal gridding is a common practice and consists in representing the reservoir with flat grid layers. The benefit of such a grid is to allow easy vertical resolution improvements in order to get better well and contacts definitions. This description implies that the grid layers no longer fit the reservoir stratigraphy, making the
heterogeneities modelling more complex, if not inaccurate. As an alternative for those two architectures, hybrid grids combine both horizontal and stratigraphic grids: a horizontal grid section is defined in the oil rim and a stratigraphic grid is conserved in the rest of the reservoir model. Therefore, the hybrid grid allows a better representation of the vertical displacement of contacts, and more generally of water and gas phases to the wells, while preserving an accurate definition of heterogeneities in the stratigraphic section. The challenge in this grid construction is, mainly, to reproduce the heterogeneities in the horizontal section. Indeed, those, more than the gridding itself, slow water and gas fingering. To solve that problem, different gridding and upscaling considerations have been taken into account and assessed here.

**Literature review**

This study is focusing on the optimization of numerical models for representation of coning phenomena in the frame of thin oil rim exploitations. We mainly want to assess the relevance of hybrid modelling to account for water production from coning. Such a study is touching a wide range of problematic including well performances and modelling, all of which having a variety of references in the literature.

If the superiority of horizontal wells over vertical ones for coning reduction has been known for a while and analytically supported in Joshi’s (1988) [2] work, the way to represent flow potential relies on strong approximations and differs from one author to the other. It leads to a variety of breakthrough time correlations and post-breakthrough performances solutions yielded by both analytical and semi-analytical approaches, including mainly Chaperon’s (1986) [1], Karcher et al’s (1986) [3] or Papatzacos et al’s (1991) [6]. Those approaches can constitute a first step for performance prediction. However, full field models are found to be a necessary tool for production optimization, for oil rim production management being highly sensitive to coning. Few studies involve hybrid gridding for thin oil rim modelling (with a horizontal section in the oil rim). A hybrid grid model showed good potential for history matching on the well-documented Troll field (Vinje et al (2011) [10]) but the first comparison of model performances in forecasting appears in Tolstukhin and Olivier’s (2010) [9] work. Contrary to the Troll field for which the heterogeneities description is forced to be simple due to the size of the field, Tolstukhin and Olivier’s (2010) [9] work illustrates the use of advanced upscaling methods, such as transmissibility or numerical upscaling, for complex heterogeneities preservation.

**Reservoir background and reservoir modelling**

The studied field is an offshore oil and gas field of the North Sea, located in some 100m deep waters, including a normally pressured reservoir interval of small burial (1700m). This 4-way deep closure reservoir consists of high porosity/permeability early Eocene Darcean sandstone intervals interbedded with shaly baffles of several hundred metres lateral extent along with silty mixed facies layers showing poor petrophysical properties (basically no permeability). Therefore, the reservoir connectivity is good in average but the flow is mainly oriented parallel to the layers due to the horizontal baffles distribution. This reservoir contains a high viscosity (4cp) saturated oil forming an oil rim about 21m thick with a transition zone of up to two metres. The gas column is small (~20m) and the reservoir pressure is supported by a large aquifer.

The oil rim development strategy implies the drilling of 4 horizontal drains up to 1500m long, completed in the top of the oil rim in two phases (Well 1, 3, 4 followed by Well 2 about one year later). The reservoir is supposed to produce more than 50 MStb/d at peak-oil and to reach more than 40MMStb oil cumulative along with about 900MSm³ gas cumulative (with an early gas cap bleed-off).

The high rates involved are favourable to gas and water coning development. The existing simulation model shows that the coning behaviour is highly influenced by the reservoir heterogeneities. Indeed, the shale baffles play a great role in driving the flows to the wells and in slowing water from fringing to the wells. As a consequence of this sheety architecture observed on Figure 1, particular coning features have been observed thanks to a streamline post processing of the original run in the stratigraphic grid.

![Figure 1 - Facies property on a reservoir cross section](image)

Three particular water coning features were observed at the wells and are clearly related to the heterogeneities of the reservoir (see Figure 2). The first early coning behaviour observed is a water flow rising straight to the horizontal drain through high vertical connectivity paths stochastically distributed below the drain during the facies distribution (A). The two other features
are coming straight from the aquifer leg to the well along the layers (B), the other through high vertical connectivity ways in the first place then finds its way to the well parallelly to the layers (C). Both of them are forced to flow horizontally to the wells by horizontal baffles. Those observations are crucial in a sense that they show that modelling heterogeneities in a proper way is crucial to preserve the coning behaviour that the wells are facing.

Local Grid Refinement
The first approach to get a better representation of flows and contact movements is to increase the resolution of the grid by using LGR. We have been comparing the productions in the stratigraphic case with productions in models involving a well scale LGR and a full oil rim LGR. Due to the minimum differences brought by well scale LGR, we are focusing here on oil rim scale LGR results (Figure 3). Both vertical and horizontal refinements have been tested. Vertical refinement is useful for flat cells; it reduces the numerical dispersion for vertical flows. Lateral refinements are more consistent with our study as the flow is mainly oriented along the layers and numerical dispersion in that direction is reduced. It is also useful in dipping cells at the vicinity of contacts as the resolution to represent the contact is enhanced. The results for these LGR runs are illustrated in Figure 4 in comparison with the original coarse case (dotted lines).

![Figure 2 - Identified coning features on streamlines post processing on the stratigraphic model](image)

![Figure 3 - Horizontal (left) and vertical LGR (right) on the oil rim scale](image)

![Figure 4 - Full field early time recoveries on oil rim scale LGR runs (vertical LGR in orange, horizontal LGR in green and red)](image)
The final results of those runs show that local grid refinements, at a big scale, have a small effect on the recoveries (2.5% oil cumulative loss with a horizontal refinement after 18 years of production, the end of the run). The effect of the refinements can be noted on a well-scale. Taking a well being on a gas rate control from start-up, we can assess the breakthrough time for water (well water cut vs. well oil production cumulative). Figure 5 and Figure 6 is showing an early water breakthrough on Well 3 for the coarse grid and a delayed water breakthrough for the horizontally refined grid. This result can be interpreted as a combination of a reduction of the numerical dispersion effects and the widening of the water cone in the horizontal refinement case. Indeed, the resolution of the grid being locally enhanced, the cone shape is refined (Figure 5). The cone’s shape refinement requires more water volume to rise to the well to reach breakthrough, consequently delaying it. In addition, it has been noticed that the coning development can be quite sensitive to the grid. Indeed, Well 4 for example is showing a faster water cut development on the horizontally refined grid compared to both other grids, resulting in a reduction of oil recovery for this particular well (Figure 6). This can be interpreted again as a result of the widened cone shape, causing the upcoming waterfront to be more massive.

As a conclusion, LGR grids validates that the model is quite sensitive to the grid and let us think that a coning oriented grid could lead to significant variations in recoveries on the whole reservoir scale.

![Figure 5 - Well 3 water cone development on coarse and horizontally refined models’ sections](image)

![Figure 6 - Well 3 and 4 early water cut evolution](image)

**Static and dynamic hybrid model fitting**

The existing stratigraphic model was using a SWATINIT keyword for initialization purposes and relative permeability endpoint scaling. As the hybrid grid is going to affect the property distribution in the oil rim (porosity and permeability remapping) and because the initialization process will require an analytic definition of the initial water saturation, a consistent and grid transposable way to define relative permeability and initial water saturation was designed to fit the stratigraphic model case’s inputs and results.

**Initial water saturation**

The SWATINIT grid used was issued from a Leverett J-function. As a consequence, the water saturations can be sorted in porosity groups as it appears on Figure 7. Thus, four porosity rock types were used and capillary pressure curves were fitted to match the initial water saturation versus height above FWL distributions. The relative error of fluids in-place was found to be less than 2%.

**Relative permeability**

The definition of relative permeability originally used endpoint scaling and the SWATINIT grid as an input for endpoint selection (especially for critical water saturations). For the relative permeability to be consistent with the rock type definition...
defined by the $P_c$ initialisation and its associated critical water saturations, it has been decided to manually scale the relative permeability curve for each rock type.

The original $S_{wcr}$ values were set to the initial water saturation if SWATINIT<0.184 and to 0.184 otherwise (maximum $S_{wcr}$ issued from SCAL). To match that definition, each rock type was split in two. A first set of water relative permeability with $S_{wcr}$ similar to the one input for $P_c$ curves is used for cells with initial water saturation under 0.184 and a set with $S_{wcr}=0.184$ is used otherwise. The comparison of cells’ $S_{wcr}$ is presented on Figure 7. As the other miscellaneous points remained untouched in the endpoint scaling process, we finally end-up with 8 rock types, each one those having a particular set $k_r-P_c$.

Figure 7 - Top: Comparison original and reviewed Initial water saturation vs Height above FWL (Top) $S_{wcr}$ vs Height above FWL (Bottom)
Figure 8 shows the comparison of the original stratigraphic case with a run integrating those two modifications at field-scale and comes as a validation of our newly defined initialization and scaling of relative permeability to be used in the hybrid model.

Figure 8 - Field results comparison with and without initialization and relative permeability revisions (solid lines stand for revised run)

Hybrid grid construction workflow

The construction of a hybrid model is done in two steps. The first step is to build the hybrid grid by adding two horizontal artificial horizons (initial FWL and GOC) between which the horizontal section is going to be built. This step is critical as the layering and the zonation have to be preserved outside the horizontal section of the grid. The second step is to remap the properties into the two grid sections. If the hybrid construction has been performed properly, the remapping of the properties in the stratigraphic section is straightforward as the layers are supposed to superimpose. The challenge here is to populate the horizontal section thoroughly. As the architecture of the hybrid grid in this section is completely different from the corresponding section of the stratigraphic grid, an upscaling process has to be carried out to perform a remapping. This remapping phase is described further in this paper.

The hybrid grid has been built using a corner point gridding process. This process is done in three phases: horizon creation, zone generation and zone layering.

The stratigraphic model originally used 3 horizons to build the grid, the top reservoir, the reservoir base and an intermediary horizon corresponding to a geological marker. The hybrid grid construction requires the use of 2 additional horizons, the GOC and the FWL in our case (the FWL is used to capture the transition zone in the horizontal section, whereas no transition is defined above the GOC). A straightforward layering process in the zone generated by the geomodeller between those two horizons will easily create parallel layers. Above and below the contacts, original zones have to be preserved. For that purpose, zones crossing the entire oil zone are defined in two parts: above and below the oil zone. Horizons needed to define the “above-contacts” zone are cut by the GOC defined as base horizon. Horizons needed to define the “below-contacts” zone are cut by the FWL defined as erosional horizon. The horizon structure used in both grids is illustrated in Figure 9.

The zone definition can become challenging if, like in our case, the horizons cut in the previous phase are being used for the zone definition. In our case, an intermediary horizon was generated as conformable to the top reservoir) to define 3 zones below it, the red, blue and green shown on Figure 11. As the top reservoir has been truncated (and divided in two horizons - below and above parts), keeping a “conformable to” would create a flattened zone top. To tackle this problem, the conformable horizons created in the stratigraphic model is extracted and used as an input for the hybrid model (instead of an output of the zonation process), as depicted in Figure 10.
The same problem is encountered during the layering process and can lead to superposition issues between the stratigraphic grid layers and the hybrid grid layers. Indeed, the layering process could use a “proportional algorithm” that refers to both top and base horizons to create layers. Those two horizons might have been truncated at contacts and the same proportional layering process would lead to a totally different layer configuration. This becomes problematic for property remapping, as the geomodeller have to find a correspondence between stratigraphic layers and hybrid layers outside the oil rim (and because the baffles have to keep their locations). To tackle this problem, top surfaces of intermediary layers are being extracted from the stratigraphic grid and used as inputs for zonation (above and below the oil rim) as it is displayed on Figure 11. Then, layering is performed within each zone. The layers are consequently guided by intermediary horizons identical in both stratigraphic and hybrid grids.
Hybrid gridding implications

Well definition
In simulation software, well connection locations are defined by the centre of cells crossed by the well trajectory defined in Petrel. In the geological grid, dipping cells can have a vertical extension significantly above or below the cell centre, resulting, when the well is crossing those cells to a bad definition of the well completion depth. Regarding coning, completions located up to 5 meters away from the well trajectory can be of significant importance (see Figure 12). Making the grid horizontal in the completion zone (i.e. the oil rim) provides additional accuracy regarding the well trajectory.

Transition zone and contact definition
The consequence of introducing flat horizon in the gridding process corresponding to contacts is to make the initialization of the model in Eclipse sharp like presented on Figure 12. The contact is well defined and the transition zone definition is more accurate. One should pay attention to the fact that the contact, which is used in our model, is a free water level (where Pc=0, below the WOC), allowing the transition zone to be included in the horizontal section of the model. As the oil-gas Pc curve is set null in the model, the GOC can be used without similar care.

Pinch-out layers
The fact that horizons cross each other in the gridding process results in the creation of pinch-out layers at the border of the horizontal and the stratigraphic grids. Those pinch-out layers can actually play a role in diverting the flow. Indeed, the connection that exists between these pinch out cells are only perpendicular to the layering locally. Therefore, the connectivity resulting from those pinch-out features is weak. Nevertheless, the problem is minimized thanks to 2 Eclipse keywords: MINPV and PINCH. Pinched cells have, by structure, small pore volumes compared to “classic” cells and fall under a well calibrated threshold by MINPV while the PINCH keyword is defining a NNC across cells under the pore volume threshold. Even though the connection is still diverted vertically on the local scale, this combination of keywords minimizes the number of cells that flows have to go through (while crossing the contacts) and enhance connectivity. Furthermore, the coning features observed in the previous section advocates for a minimum impact of those pinches. It is to be emphasized that this pinch-out features are reduced with horizontal refinement, as displayed in Figure 13 where a coarse hybrid grid (HYB1) aspect is compared with an hybrid grid with a lateral resolution multiplied by 3 (HYB3, see the Property remapping section).
**Stair-casing effect**

Another consequence of the hybrid gridding is the so-called “stair-casing effect”. A continuous dipping layer is going to be replaced in the hybrid grid by a succession of stair-like horizontal grid cells. Flow along layers encouraged by high horizontal permeability in the stratigraphic model is going to turn into a succession of cell to cell flows implying vertical connection as well as horizontal ones. This stair-casing effect results in a loss of connectivity in the oil rim that can be partly compensated by permeability remapping considerations discussed later in a dedicated section.

**Properties remapping**

After the grid building process has been completed, porosity and permeability properties (facies could be useful as well) have to be remapped in the hybrid grid. As we would like to compare the two grids with all other things being equal, it is important that the hybrid grid has properties as close as possible from stratigraphic model’s properties. This is provided outside the horizontal zone by the fact that layers superimpose on each other in the two grids. As a consequence, a standard upscaling, with geometric overlapping sampling (linking a target grid layer to the most overlapping layer in the input grid), performed in the gas cap and in the aquifer will simply remap the right value for the right cell. The story is different for the oil rim zone, as one cell in the horizontal zone does not correspond to a particular cell in the stratigraphic grid. Consequently, upscaling is required to populate the horizontal zone. As permeability upscaling requires more advanced upscaling techniques compared with facies and porosity, it is treated independently further.

Porosity and facies remapping

Porosity upsampling is basically relying on averaging methods and in our case on a straightforward arithmetic average (bulk volume weighted) as zero porosity cells have to be accounted for. The challenge here does not lie in the averaging technique but in the cell sampling. Similarly, the facies property has been upscaled thanks to a “most of” input cells bulk volume as this property is visually good to assess the consistency of the cell sampling of the upscaling.

Different sampling techniques have been tested and give poor results because heterogeneities are present in the stratigraphic models as thin dipping baffles of a few to a dozen of cells of lateral extent. They inevitably end up being faded amongst permeable and porous cells. But these heterogeneities play a great role in slowing down the water production and are driving the coning behaviour.

To tackle this problem, the sampling method has to be improved. Two means have been combined to get a better sampling as illustrated in Figure 14. The hybrid grid (target grid) can be horizontally refined, as performed in the Troll hybrid model [10], and result in an enhanced resolution more able to seize heterogeneities. The input grid (stratigraphic grid) lateral resolution can be improved as well to make the sampling by source cell centres more precise, as depicted in Figure 14 (bottom).

![Figure 14 - Refinement process for enhanced remapping (input grid is tilted, target grid is horizontal)](image)

For the purpose of optimizing the balance between property remapping quality and simulation cells count, several degrees of lateral refinement are studied. 4 hybrid models have been built: HYB1, HYB2, HYB3 and HYB5. These grids correspond to laterally refined hybrid models (cells dimension from the original stratigraphic grid are divided by 1,2,3,5 in x- and y-directions) with properties remapped from the same stratigraphic input grid. This stratigraphic grid has the lateral resolution of the original stratigraphic grid multiplied by 5 (properties from the original model are first remapped in this conform grid), to account for the reservoir architecture modifications resulting from the enhanced resolution of the surfaces used for the skeleton building. HYB1 grid has been given up quickly due to the inaccuracy of baffles modelling as well as the importance of the pinch-out layers. To get an idea of the importance of finding such a compromise, Table 1 displays the CPU time cumulative for sector models run on hybrid grids with different degrees of refinement.
Table 1 - Grid sizes and running times

<table>
<thead>
<tr>
<th>Grid</th>
<th>Active Grid cells (whole model)</th>
<th>CPU time cumulative (sector model) with 16 processors*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratigraphic grid</td>
<td>0.48M</td>
<td>6 min* (4 processors)</td>
</tr>
<tr>
<td>HYB2 grid</td>
<td>1.07M</td>
<td>27 min</td>
</tr>
<tr>
<td>HYB3 grid</td>
<td>4.60M</td>
<td>4.0 hours</td>
</tr>
<tr>
<td>HYB2 + 2 by 2 lateral LGR in the oil rim</td>
<td>~2.8M</td>
<td>27.5 hours</td>
</tr>
<tr>
<td>HYB5 grid</td>
<td>6.64M</td>
<td>36.8 hours</td>
</tr>
</tbody>
</table>

Figure 15 - Comparison of porosity grids for different grids

If the representation of the barriers looks better with refined grids, as it can be noted on Figure 15, the time of simulation also gets greater. If a coarse hybrid grid is to be used (HYB2 or HYB3) baffles have to be accounted for in the permeability grid thanks to advanced upscaling methods.

Permeability remapping

Permeability remapping raises 2 issues. First, the permeability is a diagonal tensor in the stratigraphic grid. The fact that the orientation of the grid has changed in the oil rim would cause the tensor to rotate, introducing non-diagonal terms, and modifying the diagonal terms, as presented in Wen et al (2000) [11]. The distribution of the dip angle of the Top Upper Frigg in the model (representative of the dip angle of the cells below) is concentrated between 0 and 10 degrees. The resulting permeability tensor has been kept diagonal (use of Eclipse 100) and approximated at the first order, consequently neglecting a 3% variation of the diagonal terms in the most diping cells. With \( \frac{k_v}{k_i} = 0.1 \):

\[
k = \begin{pmatrix}
  k \cos^2 \alpha + 0.1 \ k \sin^2 \alpha & 0 & 0.9 \ k \sin \alpha \cos \alpha \\
  0 & k & 0 \\
  0.9 \ k \sin \alpha \cos \alpha & 0 & 0.1 \ k \cos^2 \alpha + k \sin^2 \alpha 
\end{pmatrix} \approx \begin{pmatrix}
  k & 0 & 0 \\
  0 & k & 0 \\
  0 & 0 & 0.1 \ k
\end{pmatrix}
\]

Once it is assumed that the diagonal permeability tensor is remaining the same in both grids, upscaling has to be performed. The main objective is to keep good reservoir connectivity while preserving the heterogeneities, with a description of both baffles and sands as binary as possible. The result is pretty easy to achieve for a 5 by 5 horizontally refined grid (with a simple arithmetic average), but as the resolution is getting lower and lower, the arithmetic averaging tends to blend baffles (0 mD) with reservoir sands (several Darcies), turning to improve the reservoir connectivity. On the contrary, using a geometric or a harmonic average will tend to weight the baffles more (given a permeability of 0.001 mD for the upscaling) and to exacerbate a loss of connectivity.
For those two reasons, a more sophisticated way to remap the permeability has been investigated by performing a flow-based upscaling. This technique accounts for local preferred flow directions due to baffles and for geometry changes in the horizontal section by accounting for target cell interfaces configuration while solving local incompressible flow problems (open to flow boundaries option is used for that purpose) as depicted by Panfili et al (2010) [5]. This upscaling technique allows permeability to account for up-dip flows by considering the change in geometry of the cells (mainly the cell orientation), consequently compensating for the stair-casing effect.

In addition to the qualitative check of baffles representation, a method for quality checking the grids of permeability was inspired by the work of Tolstukhin and Olivier (2010) [9]. The process is based on streamline sector model runs involving a water injector and a producer. Contrary to this work the comparison is made between the HYB5 grid and HYB3 grid (as the streamlines are expected to be different between hybrid and stratigraphic grids). The permeability in the most refined hybrid model (HYB5) is assumed to be a reference and the QC consists in comparing the time of flight from the injector to the producer for different permeability grids to the refined hybrid reference, see Figure 16.

![Figure 16 - Sector model streamline results comparison between HYB3 permeability grids and HYB5 reference](image)

This qualitative QC of permeability grids shows a good match between the reference (HYB5 with arithmetic averaging of permeabilities) and the flow based upscaling with source cell centre sampling on HYB3 hybrid model. For those reasons, this permeability is the one that has been considered in the final hybrid model.

**Simulation results**

*Results analysis*
The simulation results presented compare on the same production schedule:
- The original model in which initialization and relative permeability scaling have been modified, as presented above;
- The hybrid model run on HYB3 grid with flow based upscaling (source cell centre sampling), in which, well PIs have been multiplied to match the base case PIs (WPIMULT keyword)
Figure 17 shows that the final hybrid model predicts less recovery than the stratigraphic model. Indeed, Well 2 suffers a 37% loss of its final cumulative oil. This loss of production is explained by its exposure to water coning due to the poor representation of the shale barriers (see Figure 18) in the hybrid grid, emphasized by the fact that this well is drilled after one year of reservoir production during which water cones have already developed. The result for this well is a faster water cut build-up compared with the stratigraphic model predictions.

Although this phenomenon is an artefact from the remapping process causing the two runs to hardly comparable, this result is still valuable. As a matter of fact, the shale baffles in the model are the result of a stochastic distribution of facies relying in many uncertain assumptions (objects’ shapes, shale frequency, trend maps, facies description...). Consequently, those results should be linked with a heterogeneity modelling sensitivity study to assess the impact on recoveries resulting from a reduction of baffles’ lateral continuity.

Figure 18 - Well 2 sections with shale baffle representation on both stratigraphic and hybrid model and ternary representation of fluids after 2 months of production
Results discussion

In order to evaluate the relevance of those results, we have tried to compare them with actual field data. No well test has been performed on the reservoir studied meaning that no data for water production is available. Good field analogue candidates in the North Sea like Balder, Grane or Gannet reservoirs exist but do not have public well data available. To cope with this lack of data, well-documented fields as Helder or Troll have been used, even if they do not exactly behave as analogues to our reservoir. The data mentioned here comes from public references: Tiefenthal (1994) [8], Murphy (1990) [4] and Vinje et al (2011) [10]. Characteristics of the reservoir and wells used in this section are summarized in Table 2.

A first qualitative comparison consists in superposing well water cut versus liquid cumulative curves from both Helder and Troll field horizontal wells to our wells’ curves. Our well’s behaviour is, as expected, located between both references (well 2 producing water from the beginning is not being compared with Helder’s case). Indeed, the mobility ratio for Helder’s well suggest a faster water cut increase compared to ours; whereas Troll slow water cut increase is explained by its “limited supply from the aquifer” (Seines et al. (1994) [7]).

Table 2 - Compared well’s reservoir characteristics

<table>
<thead>
<tr>
<th></th>
<th>Troll West oil province</th>
<th>Troll West gas province</th>
<th>Helder</th>
<th>Studied Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil gravity (°API)</td>
<td>28.5</td>
<td>28.5</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>Oil viscosity (cp)</td>
<td>1.8</td>
<td>1.8</td>
<td>30</td>
<td>4.8</td>
</tr>
<tr>
<td>k_h (md)</td>
<td>6500</td>
<td>6500</td>
<td>3700</td>
<td>3500</td>
</tr>
<tr>
<td>k_w/k_h</td>
<td>0.54</td>
<td>0.54</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Oil column height (m)</td>
<td>26</td>
<td>12</td>
<td>28</td>
<td>21</td>
</tr>
<tr>
<td>Aquifer power</td>
<td>Weak</td>
<td>Weak</td>
<td>Weak</td>
<td>Powerful</td>
</tr>
<tr>
<td>Gas column height (m)</td>
<td>~20</td>
<td>~100</td>
<td>None</td>
<td>~20</td>
</tr>
<tr>
<td>Well length (m)</td>
<td>500</td>
<td>800</td>
<td>145</td>
<td>1500</td>
</tr>
<tr>
<td>Distance to the WOC</td>
<td>5</td>
<td>0.3</td>
<td>23</td>
<td>18</td>
</tr>
</tbody>
</table>

Figure 19 - Left: Qualitative water cut vs liquid cumulative comparisons to Helder and Troll wells. Right: Well 3 GOR and Water Cut

As part of an evaluation of the relevance of the results provided by the hybrid model, additional investigations enabled us to make a valuable comparison between the literature historical data and our simulation results. For that purpose, GOR data from one well of Troll West gas province and WOR data from Helder’s well have been transformed to dimensionless quantities conformly to Tiefenthal (1994) [8]. We have used Well 3 which is not located under a stratigraphic hump (low exposure to the gas cap) and therefore is similar to Helder’s well configuration (that will be considered as no flow top boundary and constant pressure boundary at WOC). Free gas production is neglected in Well 3 which seems reasonable considering the GOR evolution from water breakthrough displayed on Figure 19. Concerning Troll’s well, the GOC is acting as a constant pressure boundary, while the WOC is also treated as such (as done in this exact paper) even if this approximation is more questionable.

In that frame, we can compare the following ratios:
Model Gridding Optimization for an Oil Rim Development in the North Sea Subject to Gas and Water Coning

\[
\frac{q_w}{q_b} = \frac{\mu_i}{\sqrt{k_i \delta_{\text{water}}}} \quad \text{and} \quad \frac{q_b}{\mu_i} = \frac{\mu_i}{\sqrt{k_i \delta_{\text{water}}}}
\]

With \( q_w = q \left( \frac{\mu_i}{k_i \delta_{\text{water}}} \right) \) for water and oil phases, \( q_b = \frac{q^2}{\mu_i} \left( \frac{\mu_i}{k_i \delta_{\text{water}}} \right) \) and \( t_D = t \left( \frac{k_i \delta_{\text{water}}}{\mu_i \phi_{\text{water}}} \right) \).

A WOR_d versus \( t_D \) curve is now dependent on the mobility ratio of the displacing phase (water or gas) and oil phase and on a dimensionless parameter related to the areal influence of the well.

\[
\text{Figure 20 - Dimensionless WOR vs dimensionless time hybrid model results comparison with real field data}
\]

This comparison shows that Well 3 water cut follows the same increase as Helder’s well. This would be expected as the main difference between those two reservoirs is the oil viscosity, playing a role through the mobility ratio which is referred to as a low influence parameter on the trends described in Tiefenthal (1994) [8].

On the contrary, the Troll West gas province is differing from the modelled reservoir and Helder’s, due to its large dimensions. Therefore, the areal influence of Troll’s well is expected to be bigger (the fact that two constant pressure boundaries are considered already doubles this parameter). Indeed, Figure 20 matches the areal influence sensitivity reported in Tiefenthal’s (1994) [8] paper with an areal parameter that would be increased from Helder’s to Troll’s behaviour.

This comparison suggests that Helder’s and Troll’s wells have followed typical water cut trends for horizontal wells, respectfully of their reservoir and well characteristics. The fact that Well 3 results are showing a water cut trend in line with those comparable fields is supporting the reliability of the simulated results. One should note that this approach does not dismiss stratigraphic model results, but supports the fact that the water cut curves issued by the hybrid model are plausible.

**Conclusion**

This study has illustrated the grid sensitivity of full field recoveries in the cases of horizontal wells subject to coning. Grid modifications to get a proper representation of coning development have been implemented. It includes local grid refinements at different scales and hybrid gridding.

Local refinements, displaying an increase resolution in the oil rim zone, have shown to have a small impact on recoveries at a whole field scale. It has been confirmed that water production is a highly impeding phenomenon on recoveries.

A method for hybrid model construction has been described and a full field production scenario was run. The results of that simulation are fairly pessimistic compared with the stratigraphic model results. As horizontal LGR on a stratigraphic model are predicting a small loss of recoveries as well, the hybrid model is believed to combine both an improved flow representation and a degraded definition of reservoir heterogeneities. Nevertheless, the final result analysis shows that the field results, though pessimistic, remain in the scope of observed recoveries for comparable North Sea region fields.

Hybrid grids represent a powerful tool to produce a coning focused model as it improves the well representation and generates well defined contacts. Nevertheless, difficulties arise from this hybrid representation mostly because our study was based on a unique stratigraphic representation that had to be reproduced in a totally different hybrid architecture. A precise model definition is needed for the reproduction of the stratigraphic zones, while high degrees of lateral refinements and advances remapping considerations are needed to preserve model heterogeneities (through permeability) in the horizontal zone. The quality checking of the hybrid model turns out to be problematic because of the lack of a hybrid model considered
as a reference (a geological model would play that role in a stratigraphic representation). As a conclusion, hybrid models are to be used in advanced coning focused studies where stratigraphic representation is believed to bias flows simulation. Furthermore, the use of a hybrid model appears to be more suited to history matching studies than instance to predictive studies for which model assessment quality is hazardous.

Way forward
We have been considering that the lack of resolution of the horizontal section of the hybrid model was causing the simulation results to be a bit pessimistic. Producing several hybrid realizations (from several stratigraphic realizations) would probably be useful to see how sensitive the hybrid model is to the stochastic distribution of the baffles.

More time could be dedicated to the representation of those baffles that remain the main difficulty in the sheety environment that we have studied. A first approach would be to create grid properties to manually isolate grid blocks located above a baffle from grid blocks located below. A second and more sophisticated approach would be to stochastically distribute the facies directly in the hybrid grid, consequently disposing of a remapping process. This approach would require the geomodeller to consider cell coordinates rather than cell indexes, making the population process more complicated. Last but not least, the upsampling approach could lead to more satisfying results using multi-phase upscaling techniques that have not been investigated in this study.

Acknowledgements
I would like to express my gratitude to Ata Nepesov for his technical expertise and his precious advice. I thank TOTAL E&P NORGE A.S. for giving me the opportunity to carry out this study. I would also like to address special thanks to Jamal Kacer and Thomas Bognø for their availability and the constructive advice that they provided.

Nomenclature

- \( \mu_i \) = Phase i viscosity
- \( B_i \) = Phase i formation volume factor
- \( FGLIR \) = Field Gas Lift Injection Rate
- \( FGPR \) = Field Gas Production Rate
- \( FGPT \) = Field Gas Production Total
- \( FGPT_{\text{tot}} \) = Field Gas Production Total for stratigraphic model
- \( FOPR \) = Field Oil Production Rate
- \( FOPT \) = Field Oil Production Total
- \( FOPT_{\text{tot}} \) = Field Oil Production Total for stratigraphic model
- \( FWL \) = Free Water Level
- \( FWWCT \) = Field Water Cut
- \( GOC \) = Gas Oil Contact
- \( GOCD \) = Dimensionless Gas Oil Contact
- \( GOR \) = Gas Oil Ratio
- \( h_o \) = Oil column height
- \( HYB1 \) = Coarse hybrid grid
- \( HYB2 \) = 2*2 laterally refined hybrid grid
- \( HYB3 \) = 3*3 laterally refined hybrid grid
- \( k_H \) = Horizontal permeability
- \( k_r \) = Relative permeability
- \( k_v \) = vertical permeability
- \( LGR \) = Local Grid Refinement
- \( NNC \) = Non Neighbour Connection
- \( P_i \) = Capillary pressure
- \( PI \) = Productivity Index
- \( q_i \) = Phase i rate
- \( q_{i\infty} \) = Dimensionless phase i rate
- \( S_{\text{Wcr}} \) = Critical water saturation
- \( WGPR \) = Well Gas Production Rate
- \( WGPT \) = Well Gas Production Total
- \( WOC \) = Water Oil Contact
- \( WODC \) = Dimensionless Water Oil Contact
- \( WOPR \) = Well Oil Production Rate
- \( WOPT \) = Well Oil Production Total
- \( WOR \) = Water Oil Ratio
- \( WWCT \) = Well Water Cut
- \( \alpha \) = Dip angle
- \( \Delta p \) = Pressure drawdown

References
2. Joshi, S. (June 1988). Augmentation of Well Productivity with Slant and Horizontal Wells. JPT.
## LITERATURE REVIEW APPENDICE

### MILESTONES PERFORMANCES AND MODELLING OF HORIZONTAL WELLS IN OIL RIM

<table>
<thead>
<tr>
<th>SPE Paper n°</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transactions of the AIME Volume 114, Number 1</td>
<td>1935</td>
<td>An Approximate Theory of Water-coning in Oil Production</td>
<td>M. Muskat, R. D. Wyckoff</td>
<td>This paper is giving the first analytical solution for the equilibrium of a water cone thanks to a flow potential approach for steady-state flow to a vertical well.</td>
</tr>
<tr>
<td>JPT June1988</td>
<td>1988</td>
<td>Augmentation of Well Productivity with Slant and Horizontal Wells</td>
<td>S.D. Joshi.</td>
<td>Derives an equation for horizontal well productivity and its derivation. This paper is the first to derive the equivalent wellbore radius for horizontal wells leading to the comparison of vertical and horizontal well performances regarding gas- and water-coning.</td>
</tr>
<tr>
<td>19822</td>
<td>1991</td>
<td>Cone Breakthrough Time for Horizontal Wells</td>
<td>P. Papatzacos, T.R. Herring, R. Martinsen, S.M. Skjaeveland.</td>
<td>The first to derive the optimal placement for a horizontal well with double coning semi-analytically. The corresponding simultaneous breakthrough time is also computed and numerically validated at low rates.</td>
</tr>
<tr>
<td>SPE Reservoir Engineering, Volume 9, Number 4 (Nov. 1994)</td>
<td>1994</td>
<td>Supercritical Production from Horizontal Wells in Oil-Rim Reservoirs</td>
<td>S.A. Tiefenthal</td>
<td>Derives a model for post breakthrough performances and provides type-curves for oil rates, WOR and GOR in the case of a horizontal well subject to simple and double coning.</td>
</tr>
<tr>
<td>SPE Reservoir Engineering, Volume 9, Number 2 (May 1994)</td>
<td>1994</td>
<td>Troll Horizontal Well Tests Demonstrate Large Production Potential From Thin Oil Zones</td>
<td>Seines, K., Lien, S., Haug, B.</td>
<td>This paper is providing extended well test data and well performances of horizontal wells producing thin oil rims.</td>
</tr>
<tr>
<td>39548</td>
<td>1998</td>
<td>Use of New Horizontal Grids in Reservoir Simulation Models Improves the Chance of Success in Developing Marginal Thin Oil Rim Reservoirs using Horizontal Wells</td>
<td>H. Hsiu-Hsyong.</td>
<td>This is the first paper presenting the benefits of new horizontal grids for thin oil rim representation.</td>
</tr>
<tr>
<td>130454</td>
<td>2010</td>
<td>A New Approach to Thin Oil Zone Modelling In High-Dipping Multilayered Reservoirs</td>
<td>E. Tolstukhin, P. Olivier</td>
<td>This paper is providing keys for hybrid modelling and assesses its forces and weaknesses in a horizontal well designing process.</td>
</tr>
<tr>
<td>148023</td>
<td>2011</td>
<td>A New Simulation Grid Type is Demonstrated for the Giant Troll Oil and Gas Field</td>
<td>J. Vinje, R. Nybø, G. Grinestaff</td>
<td>This paper is demonstrating the power of hybrid gridding for history matching purposes and provides clues for its proper building.</td>
</tr>
</tbody>
</table>
Transactions of the AIME, Volume 114, Number 1

Title
An Approximate Theory of Water-coning in Oil Production

Authors
M. Muskat, R. D. Wyckoff

Contribution
This paper is giving a first analytical solution for the equilibrium of a water cone for vertical well producing oil using an incompressible flow potential analysis.

Objective of the paper
To analytically determine the shape of the water cone under a partially penetrating vertical well subject to water coning at equilibrium conditions.

Methodology used
The analytical resolution of the equilibrium problem is done thanks to a gravity and flow potential equilibrium. The flow potential is assumed undisturbed by the water cone beneath. The height of the cone is hereafter given thanks to a graphical analysis able to yield the critical rate given the flow potential considered.

Conclusion reached
It is possible to analytically estimate the critical rate for the cone rise in the case of a simplified flow potential considering that the cone has no influence.

Comments
Even if this paper concerns vertical wells, the flow potential approach remains the basis of all the analytical resolution for coning problems.
SPE 15377

Title
Theoretical Study of Coning Toward Horizontal and Vertical Wells in Anisotropic Formations: Subcritical and Critical Rates

Authors
I. Chaperon

Contribution
This paper yields practical values of critical flow rates for horizontal wells per unit length of horizontal section. It also derives the cone elevation as a function of the producing rate and anisotropic permeabilities. The effect of increasing anisotropy on the critical rates is analysed.

Objective of the paper
To yield results of cone elevation and critical rates for horizontal wells. To account for the effects of reservoir anisotropy.

Methodology used
Muskat’s type viscous flow potential method is used. The flow potential used for a horizontal well between no flow boundaries comes from an infinite row of vertical producers’ potential.

Conclusion reached
1) Critical rate per unit length of horizontal section increases with horizontal layer transmissivity and initial oil thickness. Vertical permeability has little influence on rate. Increasing k_v would slightly increase the critical rate and keep the crest further from the well.
2) For a vertical well, increasing k_v would cause the critical rate to decrease.
3) Critical cones come usually closer to horizontal wells but horizontal wells allow higher critical rates.
Title
Some Practical Formulas to Predict Horizontal Well Behaviour

Authors
B.J. Karcher, F.M. Giger, J. Combe

Contribution
This paper provides model comparisons of critical rates and recoveries at critical rate for horizontal and vertical wells to support analytical equations already found. Numerical recovery sensitivities on rate, mobilities and drainage radius are carried out and account for over critical production from horizontal wells.

Objective of the paper
To review the existing analytical equations for critical rates for horizontal wells along with their assumptions and to advocate for horizontal wells regarding recovery enhancement and water coning problem solving.

Methodology used
The paper presents numerical results coming from a numerical simulator computing cone equilibrium thanks to the incompressible flow potential in the case of a constant height WOC boundary below the well perforations.

Conclusion reached
1) Critical rates in the case of a horizontal rate might be multiplied by a factor of two compared with vertical wells.
2) Recoveries at near critical rates might be multiplied by a factor of three.
3) The advantage of a horizontal well over a vertical well in term of recovery is lower for favourable mobility ratios (high oil mobility).
Journal of Petroleum Technology, June 1988

Title
Augmentation of Well Productivity with Slant and Horizontal Wells

Authors
S.D. Joshi

Contribution
This paper yields an equation for the productivity of horizontal wells as a function of the drainage area ellipse parameters. Parallel to vertical well performances is done by derivation of the equivalent wellbore radius for a horizontal well. The effect of anisotropy and horizontal well eccentricity is discussed. This paper also compares coning in vertical and horizontal well in the frame of the performance equation derived.

Objective of the paper
The aim of this paper is to provide the mathematical tools for horizontal well performance calculation and to account for the effect of well placement between boundaries under steady state flow conditions. To provide a quantitative comparison of coning effects in both vertical and horizontal well cases.

Methodology used
Derivation of flows in both horizontal and vertical sections of the drainage area. Combination of both flows using an electrical analogy. Derivation of the equivalent wellbore radius of a horizontal well. Application of the Pirson’s critical rate for vertical wells with the equivalent wellbore radius.

Conclusion reached
1) Theoretical predictions for horizontal well performance equation show good agreement with electrical analogue experimental data.
2) A horizontal well can produce with significantly greater rate than horizontal wells for the same reservoir drawdown.
3) Horizontal wells are suitable for thin reservoirs, high vertical permeability and reservoir with gas- and water-coning tendencies.
SPE 19822

Title
Cone Breakthrough Time for Horizontal Wells

Authors
P. Papatzacos, T.R. Herring, R. Martinsen, S.M. Skjaeveland

Contribution
Gives a numerical confirmation of Papatzacos’ semi analytical solution for breakthrough times and critical rates in the case of simple cone and double cone breakthrough to horizontal wells completed in the oil zone.

Objective of the paper
The objective of this paper is to numerically confirm the semi analytical solution developed and to illustrate parameters sensitivity of the solution. The aim is also to get a relevant comparison of the semi-analytical solution and numerical results with actual field production results.

Methodology used
The model is using a flow potential analytical approach to determine the elevation of the water-oil interface as a function of time thanks to Ozkan’s flow potential model for finite conductivity wellbore. Commercial black oil models are used to assess the sensitivity of numerically observed breakthrough times to model parameters. This sensitivity run results are compared to the semi-analytical predictions.

Conclusion reached
1) A semi-analytical solution for breakthrough times was developed and yields results for both simple and double cone cases in the case of low production rates.
2) A simple solution for the simple-cone case is derived for relatively low production rates.
3) Simulation results are showing that the solution is valid for low production rates, when the time to breakthrough is of practical interest.
4) Theoretical results are giving results comparing actual field data for the Troll and Helder fields.
Title
Supercritical Production from Horizontal Wells in Oil-Rim Reservoirs

Authors
S.A. Tiefenthal, SPE, Shell Intl. Petroleum Mij. B.V.

Contribution
This paper is the first to provide a post breakthrough performance model for horizontal wells completed in an oil rim. Presented type-curves allow predicting post breakthrough production rates in the frame of model applicability.

Objective of the paper
To address the physical principles of the post breakthrough performances of a horizontal well in an oil rim and to present a model to predict post breakthrough production rates. To compare the model results to actual field observed data on the Troll field.

Methodology used
The gravity-drainage model yielding critical rates for horizontal wells is presented. The model is extended to supercritical rates considering the oil rate proportional to the drawdown. Oil rate type-curves are assessing the impact of the mobility ratio on the oil rate. Asymptotic water and gas production rates are estimated thanks to a pseudo-steady state equation. Early WOR and GOR type-curves are derived from numerical results and presented as type-curves.

Conclusion reached
1) Two-phase supercritical production rates can be modelled by extension of the gravity-drainage model.
2) To get a precise estimate of the supercritical oil rate. The effect of the cone shape as to be accounted for by introduction of the mobility ratio.
3) Supercritical water and gas asymptotic production can be derived from a pseudo-steady state equation. The early water and gas rates are also influenced by the restriction due to the oil zone presence.
4) Three-phase rates are given by coupling 2 two-phase models. The well location in an oil rim has a limited influence on the oil rate but impacts gas and water rates.
SPE 62928

**Title**
Full Tensor Upscaling of Geologically Complex Reservoir Descriptions

**Authors**
X-H. Wen, L.J. Durlofsky, S.-H Lee and M.G. Edwards

**Contribution**
This paper is proposing two methods to account for the rotation of the permeability tensor in an upscaling procedure of an oriented heterogeneous system.

**Objective of the paper**
The paper demonstrates the importance of representing the full permeability tensor in oriented heterogeneous reservoirs by showing the errors resulting from a diagonal tensor approximation. It wants to compare the effectiveness of two alternative techniques for upscaling the full permeability tensor (a border approach and a rotation of the tensor).

**Methodology used**
The effectiveness of the technique of upscaling is done by comparing the simulation results for oil fractional flow in a biphasic liquid run with different permeability grids using the upscaling methods presented. Special care is given to water breakthrough times.

**Conclusion reached**
1) Representing the permeability by a diagonal tensor can lead to $O(1)$ errors compared to the full tensor representation as far as recoveries are concerned.
2) The full tensor local upscaling is showing degradation with increasing grid-heterogeneities angle.
3) Improvements come from the use of “border regions” of the coarse cells in the upscaling sampling as well as from the consideration of the rotation angle in the upscaling of permeability tensor terms. The rotation procedure is considered as a better overall method.
SPE 146508

Title
Advanced Upscaling for Kashagan Reservoir Modeling

Authors
P.Panfili, A.Cominelli, M.Calabrese, C.Albertini, A.Savitskiy, G.Leoni

Contribution
This paper is presenting the transmissibility upscaling as an alternative to permeability upscaling to achieve a better modelling of complex reservoir heterogeneities.

Objective of the paper
To review the state of the art in permeability upscaling and to present the innovative technique of transmissibility upscaling.
To evaluate the performances of transmissibility upscaling in the frame of Kashagan’s complex dynamic model.

Methodology used
A review of the up-to-date techniques for permeability upscaling is performed and the workflow for transmissibility upscaling is presented in details. The performances of transmissibility upscaling are assessed by comparing fine grid runs with both transmissibility and permeability upscaled coarse grids.

Conclusion reached
1) Transmissibility upscaled models are giving better results than permeability upscaled grids that are too optimistic in the Kashagan’s case.
2) In the case of highly channelized reservoir with complex flow conditions, accurate local upscaling like transmissibility upscaling is not able to accurately reproduce the fine scale complexity.
Use of New Horizontal Grids in Reservoir Simulation Models Improves the Chance of Success in Developing Marginal Thin Oil Rim Reservoirs using Horizontal Wells

Authors
H. Hsiu-Hsyong

Contribution
This is the first paper presenting the benefits of new horizontal grids for thin oil rim representation.

Objective of the paper
To present a new technique for oil rim reservoir gridding and to demonstrate the advantages of horizontal gridding.

Methodology used
The paper is presenting the principle of the grid horizontalization and the inherent principles for representing horizontal wells and contacts in such a grid. It also presents the horizontal well placement optimization results on the horizontal grid.

Conclusion reached
1) Thin oil rim reservoirs are not properly represented by stratigraphic structure grids.
2) Horizontal grids get a better representation of coning phenomena resulting in higher field recoveries.
3) Horizontal grids can accurately predict the optimum vertical position for a horizontal well.

Comments
This paper is giving the advantages of the horizontal grid but do not really provide drawbacks. The final claim that horizontal grids give better prediction for GOR and Water cut for horizontal wells is not supported by actual field data or any theoretical model.
SPE 148023

Title
A New Simulation Grid Type is Demonstrated for the Giant Troll Oil and Gas Field

Authors
Jo Vinje, Statoil ASA; Roger Nybø, Statoil ASA; George Grinestaff, Statoil ASA

Contribution
This paper is testifying for the effectiveness of a hybrid grid for oil rim model simulation. It also briefly presents a workflow for hybrid grid construction.

Objective of the paper
This paper wants to demonstrate how a hybrid grid can be efficient to account for coning phenomena and contact evolution as an alternative to stratigraphic grids.

Methodology used
The paper is first showing the process of building a hybrid grid along with the issues associated with the use of the hybrid grid in remapping the properties. In a second time, a summary of the history matching results for different grids used on the Troll field is given, showing the superiority of the hybrid representation.

Conclusion reached
1) Thin oil rim reservoirs with dipping layers will benefit for a hybrid representation.
2) Using horizontal layers to represent dipping structure results in a lack of accuracy compared with a stratigraphic grid.
3) The history matching process in a hybrid grid is much more difficult than in a stratigraphic grid and should be performed only when a stratigraphic grid is no longer fitted for purpose.

Comments
The Troll field is very similar to our reservoir in a lot of aspects (oil viscosity, petrophysical similarities) and a good performance on the Troll field is encouraging for our study. However, the volume of the Troll reservoirs are much bigger than in our case and the heterogeneities influencing flow dynamics are not considered at the same order of magnitude and result to be simpler for the Troll field. This study is using a hybrid grid for history matching whereas we intend to use it for forecasting. The consistency of our grid is therefore more difficult to assess are we are not comparing our results to a reference.
SPE 146508

**Title**
A New Approach to Thin Oil Zone Modelling In High-Dipping Multilayered Reservoirs

**Authors**
Evgeny Tolstukhin, Statoil ASA, and Pierre Olivier, GDF SUEZ E&P Norge AS

**Contribution**
This is the first paper to report the advantages and the drawbacks of the use of a hybrid model for a thin oil rim to perform horizontal well design optimization. This paper is also providing key steps for hybrid model construction.

**Objective of the paper**
This paper is advocating for the use of hybrid model for thin oil rim modelling, especially in high-dipping layered reservoir. It provides considerations on hybrid grid constructions. Well design numerical optimization results are given in the frame of the hybrid model.

**Methodology used**
This study uses simulation results and comparison of forecast runs to demonstrate the difference between traditional gridding approaches and the hybrid approach. Forecasting and well placement optimization have been performed on the hybrid model, trusted to represent the actual reservoir flows better.

**Conclusion reached**
A hybrid grid representation of the reservoir is combining the advantages of both stratigraphic and horizontal grids (fluid contact representations, property modelling, transition zone modelling, and well trajectories).

**Comments**
Because this study do not benefit from production data for the investigated field, only theoretical and numerical arguments are advanced for justifying the superiority of the hybrid grid to represent field production.
JPT June 1990

Title
Performance of Horizontal Wells in the Helder Field

Authors
P.J. Murphy

Contribution
It illustrates the successful use of horizontal wells in Helder’s field redevelopment and the superiority of those wells compared with vertical ones. This paper is providing horizontal well production data.

Objective of the paper
The objective of this paper is to discuss the engineering aspects of horizontal drilling on Helder, the performances, the benefits and the motivation of redeveloping Helder thanks to horizontal drains.

Methodology used
The paper is presenting the Helder field. The expectations coming from horizontal redevelopment are presented in link with the pre-redevelopment performances. The results and performances of the new horizontal wells are assessed in comparison with the original expectations.

Conclusion reached
1) Horizontal wells are providing economical benefit on the Helder field by having extended the existing reserves, boosted the oil production and reduced the operating costs.
2) The PI of Helder’s horizontal wells are found to be proportional to their length.
3) High liquid rates in horizontal wells prove to be strongly adverse to water cut performances.

Comments
This paper is highly valuable as it provides an analysis of a specific horizontal well on the Helder field with completely disclosed reservoir and well characteristics.
Title
Troll Horizontal Well Tests Demonstrate Large Production Potential From Thin Oil Zones

Authors
K. Seines, S. Lien, B. Haug

Contribution
This paper demonstrates the potential of horizontal wells development for turning thin oil rims subject to gas and water coning into economical targets through the example of Troll. This paper also provides keys for extended well testing in relation with horizontal well post breakthrough performances.

Objective of the paper
To assess the performances of a horizontal well on the Troll field subject to gas and water coning throughout an extended well test analysis.

Methodology used
The results of the extended horizontal well test are analysed. The dynamic model of the corresponding Troll province has been subject to a history matching study on the results of this test. Furthermore, a comparative forecast of production between vertical and horizontal well is provided and proves the superiority of producing an oil rim from horizontal wells.

Conclusion reached
1) Troll has proven that the completion of 800m horizontal well is feasible.
2) On Troll, one horizontal well would replace the production of up to 4 vertical wells.
3) Producing at supercritical rates is proved to enhance the oil recovery for thin oil rim production.

Comments
Troll field is a giant field in off-shore Norway that has been a real success story thanks to the horizontal drilling strategy. As a consequence, Troll is the subject of many papers providing good data for analogues comparison. Troll West oil province is a potential analogue to the field that I have been studying.